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The Effect of Heating and Cooling on Scaling Laws of X-Ray Clusters

Orrarujee Muanwong

Astronomy Centre, University of Sussex, Brighton, BN1 9QJ, UK

Abstract. We present results of including heating and cooling in cosmological simulations of the Λ CDM cosmology and demonstrate their effects on scaling laws of galaxy clusters. The scaling relations when radiative cooling is included are in good agreement with observations but the fraction of cooled gas is on the upper limit allowed by observations. On the contrary, the preheating model has a more realistic cooled fraction but the scaling relations are less well reproduced.

1. Introduction

The predicted X-ray luminosity and temperature relation from self-similarity ($L_X \propto T_X^2$) is shallower than the observed one ($L_X \propto T_X^3$). The steepening of the relation implies that low temperature clusters are less luminous than they would have been if self-similarity were to hold. A physical explanation of this effect is that as the luminosity is roughly proportional to the gas density squared, there must exist processes which lower the density preferentially in low temperature clusters, hence the steepening of the relation. Such processes are for example preheating and radiative cooling of the gas.

Ponman, Cannon, & Navarro (1999) have shown that the observed core entropies of low temperature clusters are in excess of what can be achieved by gravitational collapse alone. They suggest that preheating can raise the entropy before the infall and that level of entropy is maintained during gravitational collapse. As the entropy scales as $T/n_e^{2/3}$, where n_e is the electron gas density, and the temperature of the gas is fixed by the virial temperature of the halo, the excess entropy implies a decrease in density, hence a decrease in luminosity. Energy sources which can inject energy into the intergalactic medium (IGM) are for example AGN, quasars, hypernova explosions, supernova explosions and so on. However, it is still debatable whether the energy injection efficiency of the heating sources is sufficient to provide the required entropy level.

On the other hand, radiative cooling is a process which is also important throughout the history of cluster formation. Low entropy gas, i.e. dense and cold gas, is removed from the ICM, leaving behind high entropy material. Pearce et al (2000) have shown that when radiative cooling is included, the gas is slightly heated and the luminosity is greatly reduced thus acting so as to reconcile simulations and observations.

In these Proceedings, we present results from cosmological simulations of the Λ CDM cosmology in which 3 different models are considered. In the first, 'non-radiative' model, non-adiabatic heating comes about only via shocks following gravitational collapse and the gas is not allowed to cool. The second 'cooling'

model introduces radiative cooling such that 20 percent of the gas in the box has turned into stars by the current day - a value that is higher than suggested by observations (Balogh *et al* 2001). Finally, the third 'preheating' model has both radiative cooling and an impulsive heating event in which 0.1 keV per particle is injected into the IGM at a redshift of 4. This lowers the cooled fraction down to 10 percent.

The simulations consist of 160^3 particles each of gas and dark matter within boxes of side $100 h^{-1}$ Mpc. The cosmological parameters are : density parameter, $\Omega_0 = 0.35$; cosmological constant, $\Lambda_0=0.65$, Hubble parameter, $h = H_0/100\text{km s}^{-1} \text{ Mpc}^{-1} = 0.71$ and baryon density parameter, $\Omega_b h^2 = 0.019$. The metallicities are varied with time in the form of $Z = 0.3(t/t_0)Z_\odot$, where t/t_0 is the age of the Universe in units of the current time. The objective of this is to mimic the gradual enrichment of the ICM by stars. Cluster catalogues are constructed at redshift zero. The catalogues are complete down to a cluster mass of $1.18 \times 10^{13} h^{-1} \text{ M}_\odot$ which corresponds to 500 particles of each species. Details of cluster selection criteria can be found in Muanwong *et al* (2001).

2. Results

In this section, cluster properties are compared to those observed. We calculate the X-ray properties (temperature and luminosity) in a soft X-ray band (0.3-1.5 keV) by using the cooling tables of Raymond & Smith (1977). The luminosity is then corrected to a bolometric one by assuming that the gas is isothermal. The main effect of using band-limited rather than bolometric fluxes is to raise the emission-weighted temperature of low-mass clusters slightly.

2.1. $T_X - M_{200}$ Relations

We compare the derived $T_X - M_{200}$ relations of the simulated catalogues with a compilation of observations made by Horner, Mushotzky, & Scharf (1999). By using mass estimates from galaxy velocity dispersions, X-ray temperature profiles, the isothermal β -model and the surface brightness deprojection method, they obtain different scaling laws shown as dashed lines in Figure 1.

The normalisation of the cooling simulation (triangles) is greater than that of the non-radiative simulation (squares) by about a factor of 2 at the mass of $10^{14} h^{-1} \text{ M}_\odot$. For clarity, we omit the preheating results but they lie roughly between the two. Most of the radiative cooling and preheating clusters, particularly the small systems, are hotter than their virial temperatures (solid line), in accord with expectation. Non-radiative cooling clusters are cooler compared to the virial temperatures due to emission-weighting of cold and dense gas remaining in the cluster core. The slopes of all 3 simulated catalogues are roughly 0.54. We find a good agreement between the relations from the radiative cooling model and observations, given the spread of the 4 estimates from observations.

2.2. $L_{bol} - T_X$ Relations

The effect of radiative cooling is demonstrated dramatically in terms of luminosity. The $L_{bol} - T_X$ relations of the non-radiative cooling, radiative cooling and preheating simulations are shown as squares, triangles and circles respectively

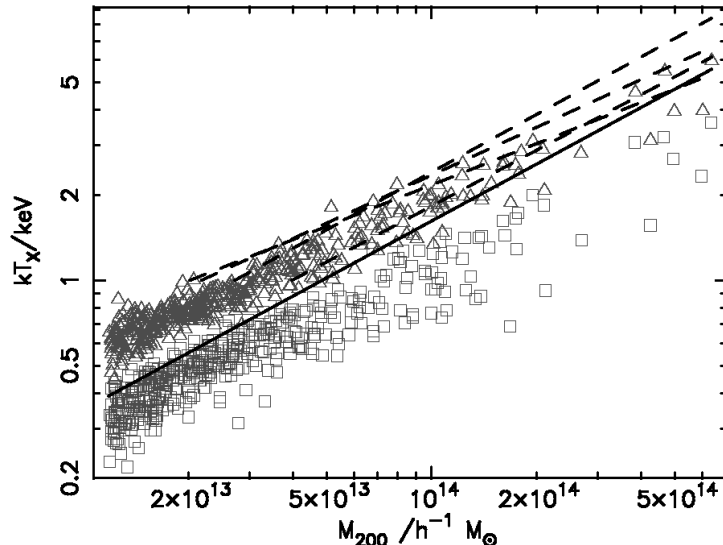


Figure 1. The temperature-mass relation. The dashed lines are from observations (Horner et al 1999). The solid line is the relation between the virial temperature and mass. Non-radiative and radiative cooling clusters are shown as squares and triangles, respectively.

in Figure 2. The large decrease in density as a result of radiative energy loss of the gas manifests in a significant reduction in luminosity. At a temperature of 1 keV, the luminosity is reduced by a factor of 100. The radiative cooling model again is found to have a good agreement with observations as shown as solid lines (Xue & Wu 200). The different solid lines are different fits to their subsamples, i.e. groups (roughly below 1 keV), clusters (above 1 keV) and a mixture of the two subsamples.

The preheating model produces a relation which lies between that of the other two models. Preheating still results in an increase in entropy, causing the normalisation of the relation to be a factor of 10 smaller than that of the non-radiative cooling simulation, but the agreement with observations is not as good as the radiative cooling simulation. The non-radiative clusters are consistent with self-similarity. The relations in the other two models are significantly steeper than 2, even more so in low temperature clusters.

3. Conclusions

We have demonstrated the effect of heating and cooling on X-ray properties of clusters in cosmological simulations. The radiative cooling model can reproduce both the temperature-mass and luminosity-temperature relations in good agreement with observations. However, the fraction of cooled gas is considerably higher than observed. In contrast, the preheating model results in a lower cooled fraction but gives a poor match to the observed scaling relations. As a possible resolution, we are currently undertaking a simulation which includes energy feedback from supernovae.

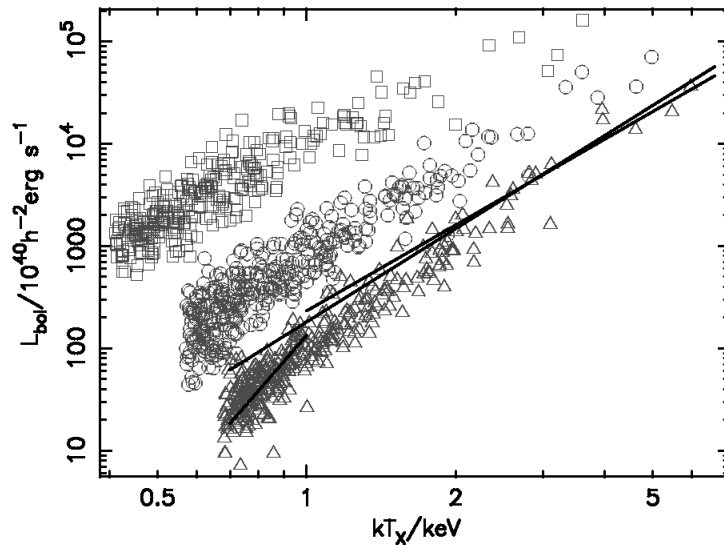


Figure 2. The luminosity-temperature relation. The solid lines are from observations (Xue & Wu 2000). Symbols are as same as those used in Figure 1. Circles represent preheated clusters.

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5. References

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